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Assessing the risk of phosphorus transfer to high ecological status rivers: Integration of nutrient management with soil geochemical and hydrological conditions.

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Abstract

Agriculture has been implicated in the loss of pristine conditions and ecology at river sites classified as at ‘high ecological status’ across Europe. Although the exact causes remain unclear, diffuse phosphorus (P) transfer warrants consideration because of its wider importance for the ecological quality of rivers. This study assessed the risk of P loss at field scale from farms under contrasting soil conditions within three case-study catchments upstream of near-pristine river sites. Data from 39 farms showed P surpluses were common on extensive farm enterprises despite a lower P requirement and level of intensity. At field scale, data from 520 fields showed that Histic topsoils with elevated organic matter contents had low P reserves due to poor sorption capacities, and received applications of P in excess of recommended rates. On this soil type 67 % of fields recorded a field P surplus of between 1 and 31 kg ha^{-1}, accounting for 46 % of fields surveyed across 10 farms in a pressured high status catchment. A P risk assessment combined nutrient management, soil biogeochemical and hydrological data at field scale, across 3 catchments and the relative risks of P transfer were highest when fertilizer quantities that exceeded current recommendations on soils with a high risk of mobilization and high risk of transport as indicated by topographic wetness index values. This situation occurred on 21 % of fields surveyed in the least intensively managed catchment with no on-farm nutrient management planning and soil testing. In contrast, the two intensively managed catchments presented a risk of P transfer in only 3 % and 1 % of fields surveyed across 29 farms. Future agri-environmental measures should be administered at field scale, not farm scale, and based on soil analysis that is inclusive of OM values on a field-by-field basis.

1. Introduction

Diffuse, non-point pollution remains a major threat to surface waters due to eutrophication caused by nitrogen (N) and phosphorus (P) transfers originating, in part, from agricultural land (Carpenter et al., 1998; EEA, 2012; OECD, 2008). In Ireland, phosphorus (P) transfer from agricultural land has been asserted as the primary cause of degradation in 53 % of the river water bodies that failed to achieve 'good' ecological status under the WFD (Byrne and Fanning, 2015). However, it is difficult to make the same assertion about rivers that are at risk of failing to maintain 'high' ecological status due to the uncertainty around the causes of degradation (Irvine and Nı´ Chuanigh, 2013; Roberts et al., 2016) and also due to natural variations in high status conditions (Irvine, 2004). Nevertheless, P transfer from agriculture does warrant consideration given its wider importance for the ecological quality of rivers.

In productive agricultural systems, nutrient transfer to surface water can be conceptualized along a continuum from source, via mobilization and delivery, to impact (Haygarth et al., 2005). Sources of P include native soil P or P applied in excess of crop demand that can be mobilized during the initial separation of P molecules from their source via geochemical desorption, biological solubilisation, or physical detachment. These processes can be increased under certain soil conditions and managements (Daly et al., 2001; McDowell et al., 2001). From the point of mobilisation, P is transported via subsurface or surface pathways, depending on soil hydrological conditions, until it is "delivered" to the water where it can have an "impact" by stimulating excessive algal growth (Beven et al., 2005; Haygarth et al., 2005).

In the European Union (EU), designations under the Water Framework Directive (WFD - OJEC, 2000) include those water bodies deemed at 'high status', i.e. not deviating from pristine or reference conditions according to ecological classifications (Pardo et al., 2012), and which may be particularly sensitive to any external pressure (del Mar Sánchez-Montoya et al., 2012). The number of high status water bodies varies across the EU either due to a natural dearth of water body types or due to ubiquitous impacts that reduce the percentage number overall (Table 1 - EEA, 2012). Ireland and Austria stand out as particularly rich member states in terms of both the number of water bodies (7,401 and 5,670, respectively) and percentage at high status (both at 18%). The WFD requires member states to maintain high status water bodies and convergence to at least good status for all other water bodies using the same harmonised ecological classification system (ECOSTAT, 2003). This harmonization is based on all EU member states calibrating biological indicators with physico-chemical parameters and based on river typologies.

A key concept underlying the WFD is the integration of existing water policies such as the Nitrates Directive (OJEC, 1991) which is designed to improve water quality by regulating on-farm nutrient use and reduce nutrient and sediment losses to water. To transpose this complex legislation into law, each EU member state must implement measures through a Nitrates Action Programme (NAP) either in specific zones or on a whole territory basis (OJEC, 1991). For example, Ireland's NAP sets limits on P use and requires farms to maintain a zero farm-gate P balance with optimised soil test P (Morgan's P < 8 mg l^{-1}) values across the farm (SI 31 of 2014). On intensive farms these measures have resulted in reducing P balances at farm scale and reducing the occurance of fields with excessive soil test P values; however, they fail to account for soil geochemical and hydrological conditions that vary spatially across the agricultural landscape. High ecological status river catchments located in upland areas with a mosaic of mineral and organic soils support a mix of extensive and intensive farm enterprises (Irvine and Nı´ Chuanigh, 2013; White et al., 2014). Whilst current legislation regulates nutrient use at farm scale, agri-environmental measures in these areas need to take account of soil geochemical and hydrological variation at smaller scales (field) to minimize nutrient losses to water and maintain high ecological status.

Grassland agriculture in Irish high status catchments varies greatly in extent from being completely absent to covering up to 88 % of catchment areas. The latter catchments are at the highest risk of failing to maintain high ecological status (Roberts et al., 2016). However, several studies have found a high proportion of fields on low intensity farms with excessive P levels due to surplus P applications over time (Gibbons et al., 2014; Schulte et al., 2009). This risk of P transfer would be elevated further when P surpluses are applied to P saturated soils and soils with poor P retention capacities. Grassland soils that cannot assimilate added P and build up P reserves for draw down by a growing crop have been characterised in Ireland and elsewhere (refs). These include soils with a high % of organic matter (OM) in the surface horizon and categorised here as Histic topsoils. High organic matter content in the surface horizon of soils occludes sorption sites on clay minerals and competes with P for sorption, thereby reducing the soils P sorption capacity and P retention. The implications for P management on these soils centers on their low P sorption capacity which prevents build-up of P reserves onto the soil matrix. Instead, P remains in the soil solution and added fertiliser P is susceptible to leaching and runoff (Daly et al., 2001; Guppy et al., 2005). In addition, if these soils coincide with conditions that promote saturation excess overland flow such as high water tables, large contributing areas and shallow slopes (Beven and Kirkby, 1979; Holden, 2006), there is likely to be a high potential for P transport to streams. However, the importance of these factors have not always been fully appreciated in previous risk assessments or nutrient management approaches for P transfer, which may have, in part, led to the perception that only intensive agriculture with high fertilizer inputs and high stocking rates and/or tillage frequencies can pose a threat to aquatic ecosystems (Doody et al., 2014, 2012; Watson et al., 2009).

Building on this background the objectives of this research were to 1) characterise the geochemical and hydrological setting for agriculture in high status catchments in Ireland, and 2) assess current nutrient management at field scale and the relative risk of P loss under different biogeochemical and hydrological condition. To address these objectives, field-scale nutrient management data and soil geochemical and hydrological characteristics were collected from 520 fields surveyed within three case study catchments. Field-scale P requirements, P applications, and P balances were examined along with field characteristics and combined in a field based risk assessment scheme to explore the extent to which current nutrient management practice poses a risk in high status catchments.

2. Methods

2.1 Characterisation of high status catchments

Three case study catchments were selected from an existing database on 508 high status catchments delineated in Roberts et al. (2016). Catchment selection used a simple multi-criteria decision approach to represent agriculture on the dominant soils across the wider high status catchment population. Of the 508 high status catchments those that had monitoring sites situated below 200 m in elevation and on river segments with Strahler stream orders ranging from 2 to 5 were selected for further analysis. Further analysis was initially by K-means cluster analysis, which aims to partition observations into a number of pre-specified clusters in which each observation belongs to the cluster with the nearest mean. In this case, K-means cluster analysis was used to identify the three main groups of catchments based on soils mapped and categoried in Teagasc/EPA Indicative Soils Map (http://gis.epa.ie/GetData/Download). These were characterised by a high percentage cover of either, poorly drained acid mineral/peaty mineral soils, well-drained acid mineral soils, and peat soils as previously mapped in the Teagasc/EPA soils and subsoils map, and these are listed in Table 2. To help select the three study catchments and to ensure they were agriculturally pressured, the 356 catchments were ranked by percentage agricultural cover three times, each time in combination with one of the three soil classes. The final three catchments were selected by expert judgement by avoiding excessively large or small catchments, catchments in inaccessible locations, and those with large urban areas or industrial workings; these were the River Allow in County Cork, the River Black in County Galway/Mayo and the River Urrin in County Wexford (Figure 1).

The upstream catchment of the River Allow is dominated by poorly drained surface water gleys underlain by siliceous drift and shale bedrock with blanket peat in the upland areas toward the river's source (Figure 2). The catchment of the River Black is dominated by well drained brown earth mineral soils underlain by calcareous drift and limestone geology but interspersed with large areas of lowland raised bog peat (Figure 2). Situated in the south east, the River Urrin catchment is dominated by well drained acid brown earth, mineral soils underlain by siliceous drift and shale and slate geology, blanket peat exist in the upland areas near to the source of the river (Figure 2).

Land use is dominated by grassland agriculture which covers 66, 63 and 41 % of the Rivers Allow, Black and Urrin catchments, respectively. For nutrient management purposes, grazing intensity in Ireland is calculated as the total annual nitrogen (kg) excreted by grazing livestock averaged over the net grassland area (grazing and silage area). 85 kg of organic nitrogen (ON) excreted annually equates to 1 livestock unit per hectare in the traditional measurement. Catchment grazing intensities are 115, 90 and 61 kg ON ha^{-1} yr^{-1}, which equates to approximately 18, 14 and 9 kg organic P ha^{-1} yr-^{1}, for the Rivers Allow, Black and

Urrin, respectively. The grassland coverage and stocking rate are lower in the River Urrin catchment due to the presence of arable land (30 %) (Figure 2).

2.2 Farm surveys

In total 10, 13 and 16 farm surveys were completed in the Allow, Black and Urrin catchments, respectively, to gather soil samples and information on farm and field nutrient management practices. These farms were selected to represent the range of farming systems present. The farms selected were also spatially distributed across the catchments to reduce the possibility for spatial auto-correlation between farm and field-scale measurements. Farmers were initially contacted through a national advisory network (Teagasc, The Irish Agriculture and Food Research Authority) and then through word of mouth, which meant that some participating farmers had no prior contact with advisory services or researchers. Across the 39 farms surveyed, a total of 520 fields (195 in the Allow, 112 in the Black, and 213 in the Urrin catchments), were sampled and records of P management were assessed. This data represented 11, 3 and 9 % of agricultural land in the rivers Allow, Black and Urrin catchments being surveyed, respectively. Thus the data reported here is not on a whole catchment basis, rather on a whole-farm basis and field-by-field basis on farms under the unique biogeochemical and hydrological settings of the selected catchments.

Soil samples were collected from each field over the 2014/2015 winter whilst ensuring at least six weeks since the last fertilizer application to allow suitable time for equilibration of fertilizer P with the soil (Agbenin and Tiessen, 1995; Vadas et al., 2007). However, farmers reported spreading 90 % of fertilizers during spring and summer leaving ample time for equilibration before sampling. Spreading of fertilizers was almost always by surface broadcasting but arable farmers often incorporated fertilizers into the soil and occasionally placed fertilizer granules with seeds. The fields were sampled by collecting at least 20 soil cores using a bucket sampler to 10 cm depth in a 'W' pattern across the field avoiding gateways and dung patches (SI 31, 2014). The cores were then composited, dried at 40 °C and sieved to 2 mm prior to laboratory analysis for chemical properties. Morgan P was used to estimate soil P (plant available) status, which involves extracting 6.5 ml of soil with a buffered (pH = 4.8) acetate-acetic acid reagent at a 1:5 (v/v) soil to solution ratio for 30 min and then analysed colorimetrically using a Camspec UV-VIS spectrometer (Byrne 1979; Morgan 1941). Soil pH was determined in deionised water at a 1:2 soil to solution ratio using a Jenway pH meter with glass electrodes. Organic matter (OM) contents were determined by loss on ignition using 5 g samples ignited for 4 hours in a Northerm muffle furnace at 400 ^{o}C. Total P was determined on 1 g sample suspended in 2 ml deionized water followed by a reagent combination of 7.5 ml nitric acid (69 %) and 2.5 ml concentrated hydrolchloric acid. Sample digestion was carried out using microwave digestion using MARS6 microwave after which samples were filtered and analysed using an Agilent inductively coupled plasma spectrometer to determine TP content. This method (Kingston and Haswell, 1997) was performed on a subset of samples categorised as Histic topsoil (n = 62) and mineral (n = 88) across all catchments.

2.3 Field scale nutrient management

To calculate field P requirements, use and balances, records collected from each field surveyed and included, organic and chemical fertilizer inputs, farm stocking densities and feed concentrate use were obtained from the farmers through a semi-structured interview and integrated with soil test P results to estimate field P requirements, applications and balances.

These were based on current advisory fertilizer guidelines, which form the basis of Ireland's National Action Programme (NAP) of measures to regulate fertilizer use for the Nitrates Directive (Coulter and Lalor, 2008). Morgan's soil P is used in Ireland for agronomic advice with levels categorised as indices; 1 (deficient), 2 (low), and 3 (agronomic optimum) and 4 (excessive) (Coulter and Lalor, 2008). The magnitude of the rates prescribed are dependent on this P index and also on factors such as farming system, intensity, organic matter contents and crop type (Coulter & Lalor 2008) the limits are described in footnotes to Table 4. The P requirement for each field is then determined as the rate identified minus feed concentrate P used per hectare of the farm. A P balance can then be calculated by then subtracting the actual amounts of P applied to individual fields as organic and chemical fertilizers to give the final balance (Murphy et al., 2015; Wall et al., 2012). These parameters were also calculated at farm scale to examine farm gate P balances for each farm surveyed.

Evidence of poaching, the damage caused to turf by the feet of livestock, was noted whilst sampling the fields These observations were then considered in relation to soil drainage properties as inferred from the Irish EPA/Teagasc Soils and Subsoils Map Indicative Soil Map (http://gis.epa.ie/GetData/Download).

Topographic wetness index (TWI - Beven and Kirkby, 1979) was calculated in ArcGIS and considered as a factor promoting P transport since slope and contributing area are key for generating saturation excess overland flow, a common generation process in temperate agricultural landscape settings (Heathwaite et al., 2005; Peukert et al., 2014). The topographic wetness index at which soil saturation actually occurs varies between studies due calculation methods or natural factors such as soil water storage capacity and preferential flow pathways, but typically occurs above the median value of indices across study areas (Leh et al., 2008; Rodhe and Seibert, 1999). For this reason, maximum TWI was determined for each field and the arbitrary threshold value for separating the fields with the driest and wettest areas was the 75th percentile of TWI values across the three catchments (hereafter termed ‘runoff potential’).

2.4 Field P risk assessments

Soil biochemical data, hydrological condition and agronomic management data for 520 fields were combined into a risk assessment scheme was to assess the relative risk of edge-of-field losses of P from each field based on source, mobilization and transport factors. The risk assessment included the field P balance as the source factor, percentage organic matter and evidence of poaching or erosion as mobilisation factors, and topographic wetness index (TWI) and surface drainage as transport factors and are described in Table 3. Each factor was assigned a weighting in terms of relative risk and combined to produce a risk score for each field. Previous field risk assessments typically only use the absolute amount of fertilizer applied to estimate the risk due to applications (e.g. Hughes et al., 2005; Lemunyon and Gilbert, 1993; Sharpley et al., 2003), which may have previously biased source risks towards intensive farms. However, because the amount of P required to replace plant offtakes (soil P requirement) varies depending on field management, a P balance approach that takes account of this may be a more accurate indicator of over-application of P. Percentage organic matter was included as a mobilisation risk factor as those soils with more than 20% organic matter have a reduced capacity adsorb any excess P applied and build up P reserves.

Assigning the risk from surface drainage involved summing the drainage density (total length as percentage of field perimeter) of streams, sloping surface ditches (>5 % slope) and flat surface ditches (<5 % slope), on the premise that higher drainage density indicates greater connectivity and a reduced potential for overland flow to re-infiltrate (Shore et al., 2013). Streams were given the highest weight (1) to reflect the risk of fields having a direct connection, sloping ditches were given an intermediate weighting (0.6) and flat ditches were given the lowest (0.3) as some sediments and P may be retained (Shore et al., 2015). Those fields scoring above the 75th percentile of drainage risk scores were assigned a high risk for surface drainage due to increased connectivity (Table 3).

Transport factors were given equal or lower weightings than source factors in many previous assessments (Lemunyon and Gilbert, 1993; e.g. Magette et al., 2007), but here overland flow risk was given the highest weighting to reflect the realisation that hydrology may be dominant in P transfer (Buda et al., 2009; Jordan et al., 2012; Mellander et al., 2015). Conversely, the connectivity risk due to surface drainage features was given a lower weighting as fields can still be connected in the absence of these features. Finally, to determine the overall risk score for each field, the risk score for each factor was multiplied by the factor weighting, the resulting risk scores for mobilisation factors were summed as were those for transport factors and then the resulting risk score for source, mobilisation and transport were multiplied in ArcGIS.

2.5 Data and statistical analysis

To examine the differences in nutrient management on fields with different biogeochemical and hydrological properties, statistical linear modelling included ‘OM’ and ‘TWI’ with two levels each as fixed factors. However, the data were arranged in a hierarchical structure as fields were nested within farms and farms were nested within catchments. This design often leads to spatial dependence, for example, fields in one farm or catchment are more similar among each other in P management than to fields on another farm or catchment due to spatial location. To account for this spatial structure, ‘farm’ and ‘catchment’ were included in the model as random factors in a nested structure to separate their effects from those of OM and

TWI. An interaction term was also included to test whether P management on fields with differing OM contents and TWI values varied depending on the catchment. All analyses were carried out using R statistical software (Version 3.2.2) with the 'nlme' and ‘Lme4’ packages (Bates 2010; Pinheiro et al. 2017). Results were considered significant when probability values were equal to or less than 0.05.

3. Results

3.1 Farm scale nutrient management planning within the case study catchments

Farm scale data are presented in Table 4. The farms surveyed in the River Black catchment ranged in size from 17 to 56 ha with an average farm size of 34 ha and were limited to mixed cattle and sheep farms with a low average grazing intensity (96 kg ON ha^{-1} ranging from 57 to 129 kg ON ha^{-1}). This was in contrast to the larger farm size and greater enterprise diversity observed in the Allow (dairy enterprises and cattle enterprises ranging in size from 11 to 84 ha with an average size of 46 ha and grazing intensity of 155 kg ON ha^{-1} ranging from 69 to 243 kg ON ha^{-1}) and River Urrin catchments (dairy, cattle, cattle and sheep, arable, and arable and sheep farms ranging in size from 15 to 78 ha with an average size of 39 ha and average grazing intensity of 154 kg ON ha^{-1} ranging from 43 to 250 kg ON ha^{-1}.

The results from the farm surveys revealed that none of the ten farmers participating in the river Black catchment had up-to-date nutrient management plans based on soil testing, whereas 8 of the 13 and 11 of the 16 farmers surveyed in the Allow and Urrin catchments, respectively, did. This was mainly because dairy farmers were farming at grazing intensities above 170 kg ON ha^{-1} and soil testing is mandatory at this intensity. This was reflected in their farm gate P balances in which most of the farms in Allow and Urrin catchments recorded negative P balances (Table 4). In contrast, 6 of the 10 farms in the Black catchment recorded positive farm gate P balances, despite a lower P requirement and level of intensity at farm scale. At this scale, the P requirement was lowest for farms in the Black catchment, and highest for those in the Urrin catchments, possibly due to the presence of cropping systems in the Urrin which have higher P requirements for arable crops than grassland. Despite good uptake of soil testing on farms in the Allow and Urrin catchments, soil pH was suboptimum in 89 % of surveyed fields and the distribution of P around the fields within farms according to nutrient guidelines was poor in all catchments, indicating poor adoption and implementation of plans where they existed.

3.2 Field scale soil P and P management

Nutrient management and soil data at field scale are presented in Table 4 and follow a broadly similar pattern to farm scale observations in P balances and requirement. Compared to the other two catchments, fields in the Black catchment had lower P requirements largely due to lower grazing intensities, as mentioned earlier, but also because of the presence of Histic topsoils on these farms. These soils are characterised with poor P retention and sorption capacities, with > 20 % OM in the top 10 cm as previously reported by Daly et al. (2001). Soil OM analysis allowed for the identification of these fields across the farms surveyed.

Using the complete field dataset, Morgan P, P applications, P requirement and P balance were delineated for both mineral (≤20 % OM) and Histic topsoils (>20 % OM) for statistical linear modelling and these values are displayed in Table 5. Although the surveyed fields represented only a relatively small sample of fields from the catchments, the observed differences in P management on fields with delineated as mineral and Histic topsoil (based on means and standard errors) were validated statistically by linear modelling. The P requirement of the fields dominated by Histic topsoils were significantly lower than for those dominated by mineral soils because of lower grazing intensities, and because of limitations on P applications on this soil type. Fields characterised as Histic topsoils have lower P recommendations than mineral soils and current recommended P applications on Histic topsoils is limited to application that replace P removed in crop offtakes, known as 'maintenance rates'.

Despite this, these fields received applications in excess of the advised maintenance rates and hence had increased and largely positive P balances (Table 5). When nutrient management is displayed by OM contents within each catchment (Figure 3) the highest number of Histic topsoils soils were found in the River Black catchment indicating highest risk of P mobilization from farms under these catchment conditions. Across the fields surveyed in the Black catchment, % OM ranged from 8 to 91 %, with 46 % of fields surveyed categorized as Histic topsoils with > 20 % OM. The absence of field-by-field soil testing to identify parts of the farm where Histic topsoils occur coupled with a lack of nutrient management planning, led to over applications of P which resulted in positive farm gate and field P balances in the Black catchment. Across the 10 farms surveyed in this catchment, 65 % of fields with Histic topsoils recorded field P balances, in surplus, ranging from 1 to 31 kg ha^{-1}.

Statistical analysis also indicated significantly higher Morgan's P values recorded in Histic topsoils (Table 5) compared to mineral soils with < 20 % OM. In the subset of soils analysed for total P, Morgan P results for Histic topsoils soils ranged from 1.4 to 40.3 mg l^{-1} with a mean value of 9.8 mg l^{-1} indicating higher P status in these soils compared to mineral soils whose values ranged from 0.9 to 29.5 mg l^{-1}, with a mean of 4.9 mg l^{-1}. High Morgan's P values typically indicates build-up of P with values above 8 mg l^{-1} indicative of elevated soil P and high P reserves in mineral soils. However, TP concentrations for Histic topsoils ranged from 65 to 1235 mg l^{-1} (mean: 505 mg l^{-1}), lower than concentrations for mineral soils which ranged from 308 to 1754 mg l^{-1} (mean: 797 mg l^{-1}). In addition, TP and Morgan's P were correlated in mineral soils ($r = 0.84$, $P < 0.001$), however there was no significant correlation (Pearson) between P parameters values in Histic topsoils ($r = 0.00$, $P > 0.05$) (Figure 4). These findings indicate a lack of accumulation as P reserves in Histic top soils due to their low sorption capacities and P retention. This indicates that Morgan's P test is over-estimating P availability and accumulation, possibly because organic P forms are hydrolysed by the acid matrix of the reagent. In addition, it is suggested here that soluble organic matter in the Morgan's extract may cause interference with the colorimetric step which affects the accuracy of the test for agronomic recommendations. Morgan P test is therefore not appropriate for soils where % OM > 20 at the surface 10 cm, and does not provide an accurate reflection of P status and for P balance estimates in nutrient management planning

3.3 Soil hydrological conditions influencing P loss risk

The mobilisation potential associated with poaching was lowest in the extensively farmed River Black catchment since only one of the surveyed fields showed clear evidence of poaching. However, 11 and 6 % of the fields surveyed in the River Allow and Urrin catchments exhibited evidence of poached soils, respectively; typically occurring around gateways, feeding and drinking troughs, and points where cattle could access the stream.

Specific field survey data were also investigated by TWI indices which theoretically esstimated the driest and wettest fields. Field data was separated by TWI and data for Morgan P, P requirement, P applied and P balance for the driest and wettest soils are shown in Table 5. Statistical linear modelling indicated that in the overall data and within individual catchments, Morgan P, P requirements, P use, and P balances were similar on fields with driest soils as they were on fields with the wettest soils, as confirmed by probability values greater than 0.05 for main effects and interactions (Table 5). When calculated at field scale, these estimates indicated that the river Black catchment showed the highest number of fields with a high runoff potential (n = 54) followed by the Allow catchment (n = 48) and then the Urrin catchment (n = 30). When calculated at whole catchment scale, TWI means and medians also followed this same order as above. Compared to the other two catchments, slopes are relatively shallow and contributing areas large in the River Black catchment, and the large areas of lowland raised bog are also indicative of wet conditions. In both the Allow and Urrin catchments, where slopes were steeper, wetness indices were generally highest around tributary streams, and in the Allow catchment also around the shallow slopes of the flood plain of the main stem of the river, a landscape feature that was much less defined in the Urrin catchment.

Artificial and natural surface drainage features also increased P transfer risk by potentially increasing connectivity between any overland flow generated and the stream. As a result, 48, 37 and 18 % of fields surveyed in the Rivers Allow, Black and Urrin catchments, respectively, achieved high drainage risk scores in the assessment. Risks were most elevated in the River Allow catchment due to shallow ditches, steep ditches and streams surrounding an average of 6.3%, 4.0% and 7.3% of field perimeters, respectively. There were no steep ditches observed in the River Black catchment, but an average of 12.4 and 5.3% of field perimeters were bordered by shallow ditches and streams, respectively. Although the artificial drainage density was extremely low in the River Urrin catchment the overall risks were elevated due to an average of 3.9% of field perimeters being bordered by streams.

3.4 Risk Assessment Scores

Fields surveyed in the River Black catchment had the highest median and widest range of field risk scores, followed by fields in the River Allow Catchment and then those in the River Urrin catchment (Figure 5). The highest risks were assumed where elevated P sources (P index 4 or positive P balances), a high potential for mobilisation (Histic soils or poached soils) and a high potential for transport (high TWI indices indicating high runoff potential) combined to form critical source areas, a situation that occurred in 3, 21 and 1 % of surveyed fields in the Allow, Black and Urrin, respectively. Inside those areas mean values of Morgan's P, P balance, OM and TWI were 11.8 mg l^{-1}, 7.5 kg ha^{-1}, 44.2 % and 17.9, respectively, compared outside of those areas where they were 5.1 mg l^{-1}, -6.0 kg ha^{-1}, 13.9 % and 14.1, respectively.

4. Discussion

Based on a carefully selected series of case study of catchments, this study shows that agriculture in pressured high ecological status catchments is not limited to intensive farming but instead exists at a range of intensities and systmes that vary greatly within and between catchments. In this present study the spatial analysis of high status catchments in Ireland revealed a mix of well-drained and poorly drained mineral soils and Histic topsoils with elevated % OM values at the surface. In this data, OM ranged from 5 % to 91 % which has implication for the assimilation and retention of added P and the risk of P loss to water. Risks of P transfer were present across these ranges, but were particularly high within the River Black catchment, which contained the lower intensity drystock farms. Schulte et al. (2009) uncovered a similar situation in the Lough Melvin catchment, Northern Ireland, a catchment with a grazing intensity of approximately 41 kg ON ha^{-1}, where 31 % of fields surveyed posed a high risk of P transfer (using the risk assessment approach of Magette et al. (2007)).

4.1 Nutrient management practice in high status catchments

The adoption of soil testing and farm nutrient management plans also varied, with none of the farms in the most extensively farmed Black catchment currently using soil testing or nutrient management planning as a tool to manage nutrients, whereas most of the farms in the more intensively farmed catchment had adopted nutrient management planning based on soil testing.

Phosphorus applications above the recommended rates were common in the extensively managed River Black catchment on Histic topsoils as indicated by positive P balances. While other studies indicate that farm-scale P balances in Ireland have declined since the introduction of the Nitrates Directive measures (Buckley et al., 2016; Mihailescu et al., 2015; Ruane et al., 2043), the results of this study showed that positive P balances occurred when nutrient management failed to take account of soil type, specifically, soils with OM > 20 % within the agronomic depth for soil sampling. In line with previous studies (Wall et al., 2012) poor nutrient management and the absence of on-farm nutrient management planning gave rise to poor distribution of nutrients across the farm resulting in fields with excessively high P values receiving P applications. Previous studies focusing on intensively farmed agricultural catchments, with predominantly mineral soils, have demonstrated that elevated soil P levels can be corrected with regular soil testing and nutrient management planning. However, this approach will only work in high status catchments if soil analysis for agronomic recommendations includes % OM testing on a field-by-field basis so that Histic topsoils can be identified from mineral soils and on-farm nutrient management tailored for soil type.

4.2 Soil testing on mineral and Histic topsoils

Nutrient management planning and the regulation of P use on farms is inextricably linked with soil testing, however, this has resulted in an over-reliance of testing for P and pH only to guide nutrient applications and record farm-gate P balances. Relying on Morgan's P values alone, without including organic matter values, masks the effect of soil type on recommended P rates, P balance and P loss risk as illustrated by the data collected in this study. Where soil samples exhibit > 20 % OM current nutrient management guidelines recommend P applications that replace crop offtakes, and prohibits build-up rates on these soils, due to poor P sorption capacities (Coulter and Lalor, 2008; Daly et al., 2001). An important step towards accounting for this issue has been the incorporation of OM into fertilizer recommendations in Ireland and in other European countries (Amery and Schoumans, 2014; Coulter and Lalor, 2008; Jordan-Meille et al., 2012). In Ireland rates of P that replace P removed in crop offtakes, known as maintenance rates are permitted, however, the occurance of Histic topsoils across farms in high status catchments will only be identified by soil sampling and analysis that includes % OM as a parameter. Soil analysis that does not include % OM will not allow for delineation of Histic topsoils on the farm and will lead to misguided over-applications of P to these soils. For mineral soils P applications are guided by soil test P levels and corresponding P index, however, as there is currently no P index system for Histic topsoils, rates of P applied rely on the inclusion of % OM in soil analytical suites.

Positive P balances on Histic topsoils occurred in 67 % of fields surveyed and ranged from surpluses of between 1 and 31 kg P ha^{-1}. The reasons for this were two-fold: Firstly, the absence of soil testing to identify the occurance of these soils across the farm and secondly, the lack of nutrient management plans to guide P application meant that P was applied in excess of recommended rates, often at rates typically applied to build-up soil P reserves on mineral soil. Losses of applied P from these soils can be high, for example, McDowell and Monaghan (2015) studied P losses from managed pastures on podzol and peat soils in New Zealand. Although P loads from the podzol soils were high (>8 kg ha^{-1}) over the 18 month study period, they were extreme from the peat soil (80 kg ha^{-1}) equalling 89 % of the fertilizer P applied. Previous studies in Ireland and elsewhere (Daly et al., 2001; Guppy et al., 2005) have characterised these soils with low P sorption capacities and poor P retention due to competitive reactions between organic matter and P on the surface of clay minerals. This means that these soils cannot build up P reserves and retain added P through the physico-chemical reactions that typically happen in mineral soils. The results from this study demonstrated an absence of accumulation in total P concentrations for Histic topsoils despite the application of P build-up rates indicative of these soils inability to build up P reserves and their potential for high P losses of applied P (Simmonds et al., 2015).

4.3 Field Soil hydrological conditions in high status catchments

The Allow catchment recorded a relatively higher incidence of soil disturbance by poaching of soil by livestock. Amongst other effects poaching of the soil damages the protective cover that would otherwise be provided by vegetation and therefore leaves the soil vulnerable to erosion (Bilotta et al., 2008; Haygarth et al., 2012; McDowell et al., 2003). For example, on a hillslope in the UK the removal of the vegetation cover through severe poaching led to an increase in the rate of suspended sediment and total phosphorus delivery in overland flow by 30 and 16 times, respectively (Heathwaite et al., 1990). Poorly drained soils are most susceptible (Creamer et al., 2010; Heathwaite et al., 1990), and fields in the Allow catchment where these soils were common and grazing intensities high, showed the greatest incidence of poaching, increasing the risk of sediment delivery into streams and rivers.

Shallow sloping topography and large contributing areas promote saturation excess overland flow (Agnew et al., 2006; Beven and Kirkby, 1979), which is further exacerbated by poorly drained soils (Buda et al., 2009; Needelman et al., 2004). In terms of P transfer, these hydrological factors are thought to over-ride the effects of management. For example, Buda et al. (2009) measured P in runoff from small plots and found that overland flow volumes and P loads were larger at foot slope positions compared to at upslope positions where legacy soil P concentrations and therefore P concentrations in runoff were high, but runoff volumes were much lower. This has also been observed at the catchment scale, where catchments with flashy hydrographs, yet with lower P sources, showed the greatest stream P loads (Basset, 2010; Jordan et al., 2012; Mellander et al., 2015). Despite this importance, no European country's fertilizer guidelines currently consider soil hydrological conditions as a risk factor (Amery and Schoumans, 2014; Jordan-Meille et al., 2012), and hence field P management appeared to be similar on the driest soils as it was on the wettest soils. Although outside of nutrient management recommendations, current Irish NAP measures discourage the spreading of fertilizers on wet and sloping areas of the farm, but there is currently no formal method to identify such areas and adjust management accordingly.

4.4 Field scale risk assessment in high status catchments

Across the three catchments, the assessed relative risks of P transfer from fields was higher from fields located within the extensively farmed River Black catchment, as evidenced by the high proportion fields where high source, mobilisation and transport potentials coincided. Schulte et al. (2009) proposed a similar situation in the Irish Lough Melvin catchment with a grazing intensity of approximately 41 kg ON ha^{-1}, where 31 % of fields surveyed posed a high risk of P transfer due to over-application of slurry to drier fields and a resulting build-up of soil P above agronomic optimum levels. These results are in contrast to the intensively farmed River Urrin catchment, where the number of fields showing high risks were consistently fewer for all P transfer factors individually and combined (1 % of fields surveyed). Overall, these data question the perception that only intensive agriculture can pose a P risk to water quality and suggests that if research and policy places more focus on specific farming systems that are considered to be intensive there will be a risk of non-compliance especially in the context of maintaining high ecological status at river sites. Although this risk assessment served well to compare relative risk between catchments and fields, as with all field scale P risk assessments, there is a great deal of uncertainty around how well the measured risk actually reflects absolute risk. For example, there are a lack of data from Irish studies measuring P loss from agricultural fields with which to validate risk assessments (Hughes et al., 2005), the national DEM resolution was insufficient in resolution to identify flow sinks created by micro-topographic features that cause overland flow to become disconnected (Thomas et al., 2016) and TWI alone does not account for the soil water storage capacity, which, when low, can increase overland flow risk (Quinn et al., 1995; Walter et al., 2002). However, the greatest uncertainty relates to the issue of scale, and specifically, around how well risks identified at field scale are realized in water quality and ecological status at catchment scales.

5. Conclusions and recommendations

This study characterised the soil geochemical and hydrological properties of farms in high status catchments in Ireland and examined field scale nutrient management and the relative risk of P loss from fields, under different soil conditions Low adoption of soil testing and nutrient management planning on extensive farms led to increased risks of P transfer on Histic topsoils when application of P sources failed to account for soil conditions that promote the mobilisation and transport of P such as highly organic matter and wet soils. Furthermore, the risk assessment based on fields surveyed revealed that the catchment, with the highest occurance of Histic topsoils, (wet soil) posed the greatest risk of P loss, based on positive P balances and fields with high % OM. Current EU water policy measures for agriculture centers on nutrient management planning and soil testing on intensive farms, however, this study has illustrated the need for better nutrient use efficiency on extensive grassland farms on marginalized land. To increase nutrient use efficiency and reduce P loss risk and based on the results of this study the following recommendation include:

- Regular soil testing to monitor soil P and pH on should be used to optimize nutrient management on mineral soils, but not be relied upon for nutrient management on Histic topsoils.
- Extensive farm enterprises in high status catchments should have access to soil information on % OM on a field-by-field basis. Organic matter testing at high spatial resolution need only be carried out once to establish which parts of the farm are comprised of mineral and Histic topsoils. This will ensure that nutrient management is soil type specific and will restore P surpluses to balance at both field and farm scale.
- Hydrologically sensitive areas within high status river catchments could be delineated using simple topographic indices as done here, and the timing and rates of P applications tailored to account for risk, as is the case for high OM soils.
- Agricultural measures for high status catchments will need to be administered at field scale (not farm scale) with the aid of appropriate soil geochemical and hydrological data at this scale.

- Future agri-environmental schemes under the EU Common Agricultural Policy and Rural Development Programme could consider providing % OM surveys on a field-by-field basis to farms in high status catchments.

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Figure Captions

Figure 1. Ireland, showing county boundaries (Republic of Ireland) and the location and characteristics of the three case study catchments. Average annual rainfall and temperature are Met Éireann 10 year averages.

Figure 2. Agricultural land use (A) and soil classes (B) in the three case study catchments.

Figure 3. Mean Morgan P (A), P requirement (B), P applied (C) and P balance (D) by organic matter contents within each catchment showing standard error bars. The number of samples (*n*) used for summarising those variables were as follows: River Allow - OM ≤20 %, *n*=184; River Allow - OM >20

%, *n*=11; River Black - OM ≤20 %, *n*=61; River Black - OM >20 %, *n*=51; River Urrin - OM ≤20 %, *n*=211; River Urrin - OM >20 %, *n*=2.

Figure 4. Scatterplots of soil TP and Morgan P by organic matter (OM) contents (Mineral soils: ≤20 % OM; Histic topsoils: >20 % OM). Pearson's r correlation was only significant (r = 0.84, P <0.001) for mineral soils.

Figure 5. Box (25, 50 and 75 percentiles) and whisker (1.5 x interquartile range) plots of the risk scores by catchment.

Table 1. EU member state water body numbers, percentage and river length at high status (EEA, 2012 – www.eea.europa.eu/data-and-maps/data/wise_wfd-european-data).

EU Member State	Number of water bodies	Number at High Status	Percentage at High Status	Total length	Length at High Status	Percentage at High Status
Malta	9	4	44.4	0	0	0
Slovakia	1760	487	27.7	18944	3786	20
Lithuania	1183	287	24.3	14251	2605	18.3
Croatia	1315	281	21.4	13041	1800	13.8
Austria	7401	1332	18.0	31393	4291	13.7
Ireland	5670	1012	17.8	21039	1864	8.9
Finland	6153	681	11.1	28875	4659	16.1
Sweden	23418	2043	8.7	79467	6181	7.8
Spain	5124	425	8.3	82276	5396	6.6
Slovenia	155	11	7.1	2619	168	6.4
Greece	1689	112	6.6	13030	206	1.6
France	11523	747	6.5	241684	10881	4.5
Denmark	15988	965	6.0	18842	1436	7.6
Portugal	1945	94	4.8	598575	79628	13.3
Bulgaria	759	36	4.7	25569	862	3.4
Romania	3399	145	4.3	74473	2346	3.2
United Kingdom	10961	441	4.0	99748	1653	1.7
Cyprus	260	8	3.1	2579	0	0
Latvia	470	14	3.0	7752	535	6.9
Estonia	750	12	1.6	12107	295	2.4
Belgium	560	7	1.2	9309	95	1
Italy	8614	91	1.1	78812	655	0.8
Poland	5643	52	0.9	111485	749	0.7
Germany	9863	76	0.8	126158	152	0.1
Hungary	1082	5	0.5	18802	0	0
Czech Republic	1140	0	0.0	18596	0	0
Netherlands	724	0	0.0	4757	0	0
Luxembourg	102	0	0.0	0	0	0

Table 2. Results of K-means clustering analysis showing mean soil class coverage for the three main clusters of catchments based on soils and the overall data.

Cluster number:	1 (*n*=158)	2 (*n*=102)	3 (*n*=96)	Overall (*n*=356)
Soil class (% coverage):				
Alluvium	2.15	1.32	3.09	2.17
Acid mineral poorly drained	26.23	11.21	11.94	18.07
Acid mineral well drained	14.59	4.42	66.16	25.58
Basic mineral poorly drained	1.54	1.60	0.23	1.20
Basic mineral well drained	4.06	2.51	1.37	2.89
Acid peaty mineral poorly drained	10.54	6.25	3.94	7.53
Basic peaty mineral unclassified drainage	17.75	6.48	8.03	11.90
Basic peaty mineral poorly drained	0.26	0.58	0.07	0.30
Peat	19.87	63.88	4.48	28.33
Miscellaneous	3.00	1.76	0.70	2.02

Table 3. Structure and components of the field risk assessment.

	Factor	Description	Weighting	Low risk (1)	High risk (3)
Source	P application risk	P balance	0.8	P deficit	P surplus
*					
Mobilisation	Desorption risk	Organic matter contents	0.6	Mineral (≤20 % OM)	Histic (>20 % OM)
	+				
	Detachment risk	Grassland - poaching	0.4	No signs of poaching	Clear signs of poaching
		Grassland or Arable - erosion	0.4	No signs of erosion	Clear signs of erosion
*					
Transport	Overland flow risk	Topographic wetness index	1	Driest (≤P_{75})	Wettest (>P_{75})
	+				
	Connectivity risk	Surface drainage features	0.6	Least connected (≤P_{75})	Most connected (>P_{75})